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13. ABSTRACT *(Maximum 200 words)*

Each year, 400 million cubic yards of sediment are dredged in the United States of which 3 to 5 percent is polluted and cannot be used beneficially or returned to the environment near dredging sites. Disposal of this polluted, dredged material is a national problem. One solution to this problem is to relocate and isolate polluted dredged material to the seafloor of the abyssal ocean, considered to include those depths greater than 300 m. SimDOR, a project sponsored by the Defense Advanced Research Projects Agency, focused on simulation of the scientific and technical issues involved with this disposal option.

SimDOR, which stands for Simulation of Deep Ocean Relocation of Dredged Material, concentrated primarily on sites of the abyssal seafloor of the North Atlantic Ocean and considered dredged material coming from to the eastern seaboard of the United States. Results from the SimDOR project are also generally applicable to west coast and Gulf of Mexico ports.

The SimDOR project took advantage of recent advances in numerical modeling capabilities, simulation concepts, and visualization technology. Simulations identified are predicted effects of this disposal option including the dredging and relocation procedures as well as the resulting environmental impact. Simulation of the entire process from dredging through long-term impact on the abyssal environment allowed engineers, scientists, environmentalists, and the public an opportunity to study and understand all aspects of this option. Systems to dredge sediments, load containers, transport them to the ocean site, and ensure their safe descent to the abyssal seafloor were designed, simulated and evaluated. Hydrodynamic, geochemical, and biological effects of the relocation process on scales ranging from the time of disposal of dredged material on the abyssal seafloor to years, tens of years, to thousands of years in the future were simulated and visualized. It is concluded that deep ocean relocation of polluted dredged material offers and economically sound and environmentally safe alternative to land-based waste isolation.

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DEEP OCEAN RELOCATION OF DREDGED MATERIAL: CONTAINMENT, TRANSPORTING, AND EMPLACEMENT

P. J. Valent[1], D. K. Young[2], and A. W. Green[3]

ABSTRACT

Each year, 400 million cubic yards of sediment are dredged in the United States of which 3 to 5 percent is polluted and cannot be used beneficially or returned to the environment near dredging sites. Disposal of this polluted, dredged material is a national problem. One solution to this problem is to relocate and isolate polluted dredged material to the seafloor of the abyssal ocean, considered to include those depths greater than 3000 m. SimDOR, a project sponsored by the Defense Advanced Research Projects Agency, focused on simulation of the scientific and technical issues involved with this disposal option.

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INTRODUCTION

Scope

This paper summarizes results of two years of study of the option of isolating contaminated dredged material on the abyssal seafloor, focusing on the technical aspects of containing, transporting, and placing the material. The purpose is to convey to practitioners in the dredging industry ideas generated in this study, in particular, information on the physics of free-fall of geosynthetic fabric containers. Study results of physical, chemical, and biological impacts of the dredged material placement on the abyssal environment are reported elsewhere (Valent and Young 1995; Young and Valent 1996, 1997; Valent and Young 1997; Valent et al. 1997).

Tasking

The U.S. Congress tasked the Department of Defense (DoD) in the 1993 DoD Appropriation Bill, Senate Report 102-408, as part of DoD's Strategic Environmental Research and Development Program (SERDP), to "study the advantages, disadvantages, and economic viability of storing industrial waste (defined as sewage sludge, fly ash from municipal incinerators, and contaminated dredged material) in the abyssal plains of the ocean floor." The Naval Research Laboratory (NRL) carried out this tasking from November 1993 through September 1994, reporting detailed findings in Valent and Young (1995), Valent et al. (1996), and Young and Valent (1996). The Congress again, in the 1994 DoD Appropriations Bill, directed the DoD, through its Defense Advanced Research Projects Agency, "to study the concept of deep ocean relocation or isolation of sedimentary material." NRL carried out this tasking from July 1995 through September 1996, with the detailed results of that follow-on effort reported in Young and Valent (1997), Valent and Young (1997), and Valent et al. (1997).

Please note, in these taskings the DoD was asked to assess only the technical feasibility and environmental impact of deep ocean relocation and isolation. The DoD was neither tasked to assess the acceptability of the deep ocean isolation concept with regard to U.S. Law and international agreements, such as presented by the London Dumping Convention, nor was DoD tasked to compare socio-economic impacts of the concept with those of other waste management options.

Prior Studies

A recent study addressing the deep ocean option for disposal of various waste materials, including contaminated dredged material, resulted from two workshops hosted by the Woods Hole Oceanographic Institution (WHOI) (Spencer 1991) and the Massachusetts Institute of Technology (MIT) (Chryssostomidis 1991) under the sponsorship of the Sloan Foundation. This study concluded that it was potentially possible, without detriment to humans and their environment, to dispose of sewage sludge from municipal treatment plants, fly ash from municipal incinerators, and contaminated dredged material by emplacement of these materials on the abyssal

seafloor. The WHOI-MIT workshop participants did allow that many technically and environmentally related questions required answering before proceeding with the abyssal seafloor waste management option.

This Study

Under the first DoD tasking, industry engineers and university economists evaluated and costed preliminary engineering concepts for transporting to optimal abyssal seafloor sites the same spectrum of wastes as in the WHOI-MIT study. NRL and university scientists developed preliminary models of predicted hydrodynamic, chemical and biological processes affecting potential pathways of contaminants potentially emanating from the emplaced waste deposits. Protocols for selecting sites optimized for waste isolation were established, a site selection model was executed, and a preliminary plan for surveying and monitoring such sites was developed.

The NRL study concluded that the most technologically achievable and economically feasible concept for transfer of wastes from the ocean surface to the abyssal seafloor is transfer in geosynthetic fabric containers (GFCs) free-falling from a vessel at the ocean surface. The NRL study further concluded that, given available data and modeling predictions, abyssal seafloor sites can be identified where bottom currents will not be strong enough to resuspend dredged material once placed on the seafloor. Thus, the physical dispersal mechanism for transport of included contaminants was important only for the near field (Valent and Young 1995). While the NRL study made significant progress in developing analytical models of seafloor chemical and biological processes, study participants found that available data were inadequate to properly parameterize and validate all models.

Under the second DoD tasking, focused on relocation of contaminated dredged material, an industrial engineering team examined the entire dredging-through-placement process using existing or developed models with the goal of connecting these models to produce an end-to-end simulation capability. Results of this modeling of the dredging-through-placement process are reported in this paper. Models of the physical, chemical, and biological processes and impact of placement of the containerized contaminated dredged material on those processes were improved and expanded over those of the first, SERDP study. Results of the environmental impact work are reported elsewhere (Young and Valent 1997; and Valent and Young 1997a, 1997b).

THE ENGINEERING CONCEPT

Concept of Operation

The engineering concept is divided into four functional areas: dredging, transfer and loading, transportation, and placement (Fig. 1). Design of the dredging, transfer, and loading systems sought (1) to minimize water added to the dredged material during these processes, (2) to accommodate the majority of the dredging sites in the U.S., and (3) to reduce operational costs and environmental impacts. The bulk wet density of dredged material was specified as between 1.4 and 1.7 Mg/m^3.

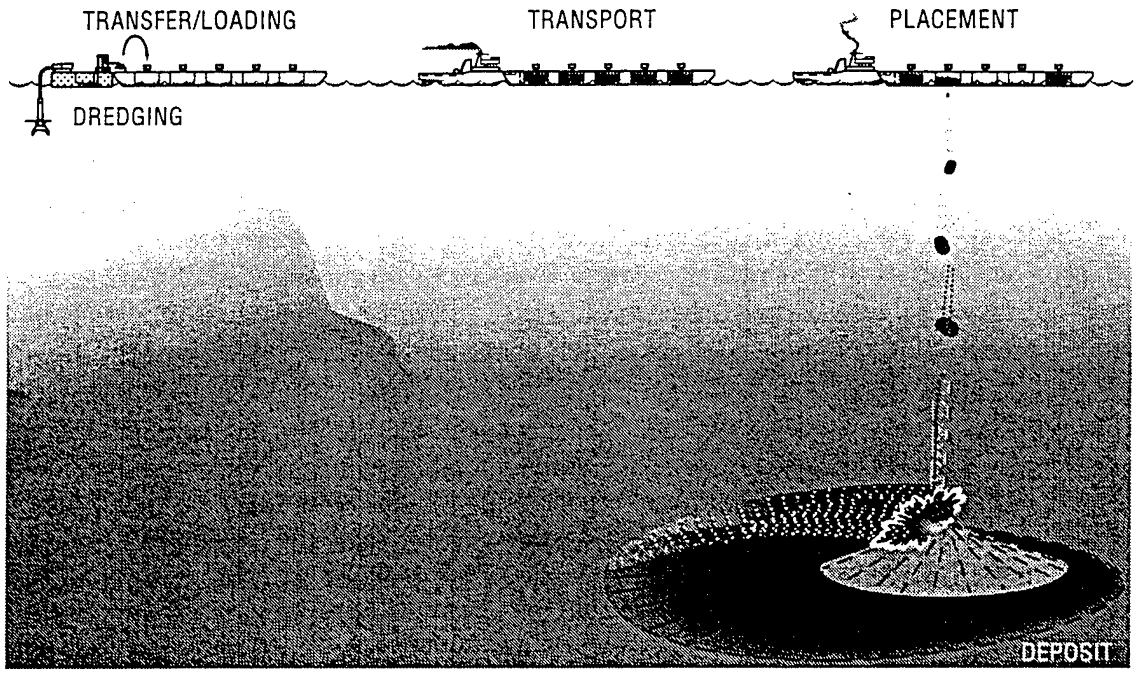

Figure 1. SimDOR systems engineering concepts.

Dredging, Transfer, and Loading

A clamshell dredge system was selected among various clean dredge systems because of its capability to dredge with minimal water added to the material and greater flexibility in debris handling. The dredger system uses two 4-m^3 (5-yd^3) closed clamshell dredges, each capable of dredging 150 m^3/hr, working side-by-side on a dredging platform (Fig. 2). The dredging platform is a modified barge platform with a central storage hopper bin for short term sediment storage of up to 300 m^3 during dredged material transfer. At the base of the storage hopper in the dredging platform, two augers (one per hopper) transfer the material into the transfer hopper. The transfer hopper is the first hopper in the distribution series and serves in transferring the sediment from the dredging platform to the transporter vessel. The hoppers in the distribution series are over-sized to accommodate a buildup of material in the event of equipment malfunction. Dredged material is transferred by the auger system from the distribution hoppers into geosynthetic fabric containers (GFCs), one GFC in each of the cargo cells. The auger system has the maximum capability of transporting dredged material at a rate of 450 m^3/hr. The time required to fill the transporter, based on one dredge clamshell operating at 150 m^3/hr, is 80.6 hr.

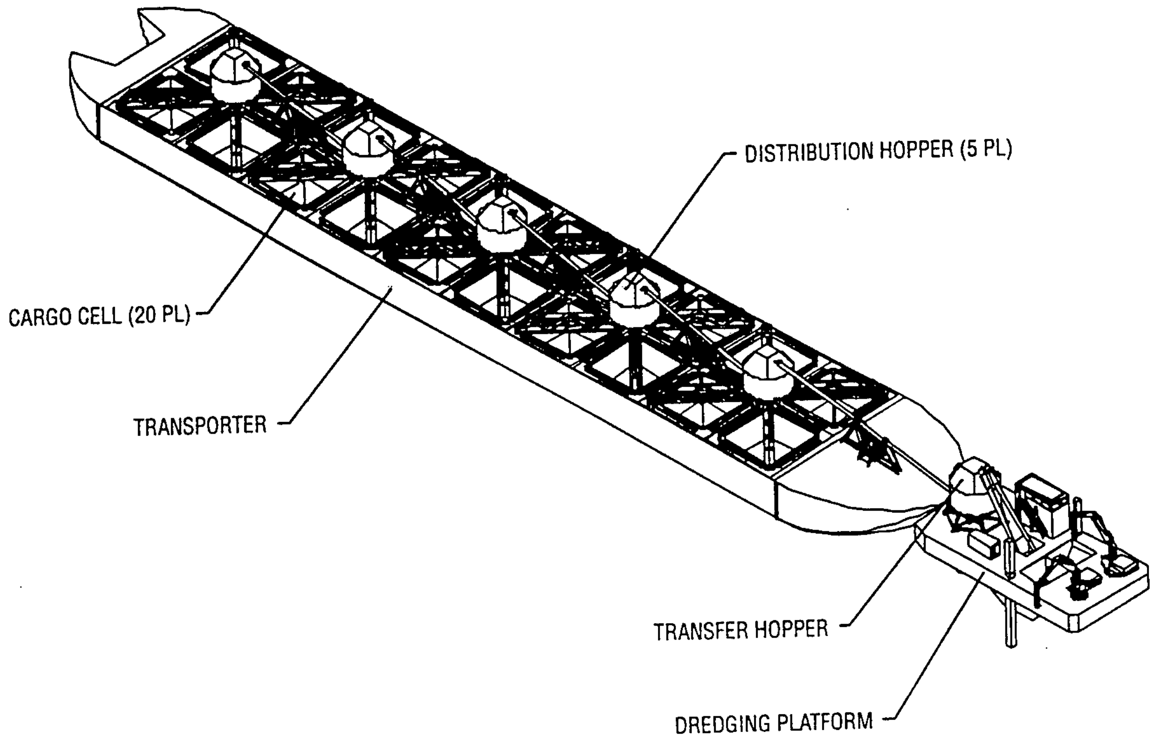

Figure 2. Schematic of dredging platform and transporter coupled for dredged material transfer and loading, oblique view.

Transport and Placement

The transporter concept selected is an integrated tug-barge (ITB) (Fig. 1) because its lower overall hydrodynamic drag offers higher average speeds, better control, efficient operation over a wide range of sea states, and better fuel economy when compared to other transport configurations. The barge contains a 10×2 array of cargo cells for transporting 19000 DWT (between 10,000–12,000 m^3 (13,000–16,000 yd^3)) of dredged material (Fig. 2). Each cargo cell has an inner compartment with bottom trap doors for releasing the containerized dredged material (Fig. 3).

Structural Configuration of Transporter

The overall dimensions of the transporter barge are 241-m (790-ft) length, 32-m (106-ft) beam, and 5.5-m (18-ft) draft. The amount of freeboard added is based on the structural strength required for maintaining sea keeping while minimizing green water on deck. The cargo cells make up 171 m (561 ft) of the midbody. The bow length is 18 m (60 ft) and stern length is 21 m (67 ft, transitioning the midbody dimensions from a block shape to a ship configuration capable of traveling a desired

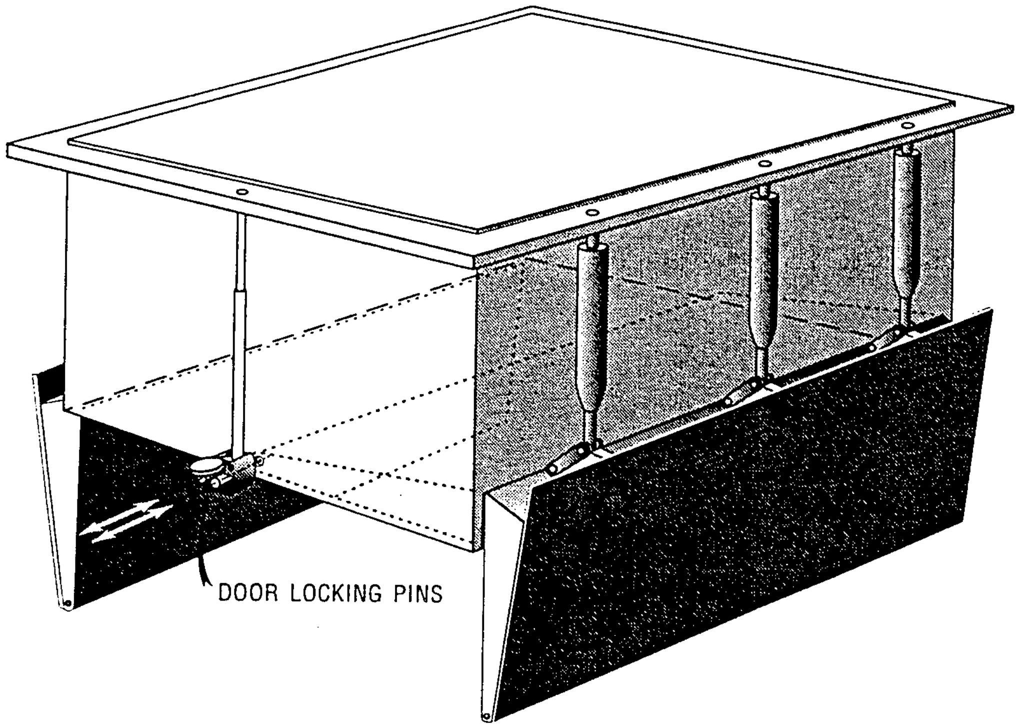

Figure 3. Compartment bottom door concept.

sustained speed of 12 knots. An integrated tug/barge connection system, such as the Intercom system, a single degree of freedom connection, would allow free relative rotational pitch motion. The connection is operable in sea states up to 5; threat of sea state 6 conditions would require disconnecting the tug and transporter and changing to a towed barge configuration.

Physics-Based Simulation of Transporter Design and Sea keeping

Sea-keeping analysis was performed using the Ship Motion Program (SMP) model. It is a two-dimensional, linear strip theory model, developed by Dr. Nils Salvesen, and widely used by the Navy.

The transporter performance was evaluated for sea state 5 and sea state 8. In this preliminary analysis, the barge was evaluated independently of the tug, since the tug (being small in size compared to the barge) will have little influence on barge motions. The sea-keeping calculation was performed for long-crested (undirectional) head seas. Figure 4 shows a single frame from an animation of the ship motions for the conventional rigid construction alternative design in sea state 5. The animation in sea state 8 (figure not shown here) predicts that the barge would be under "green water" given the design freeboard. The statistical results of the sea-keeping simulations are presented in Table 1.

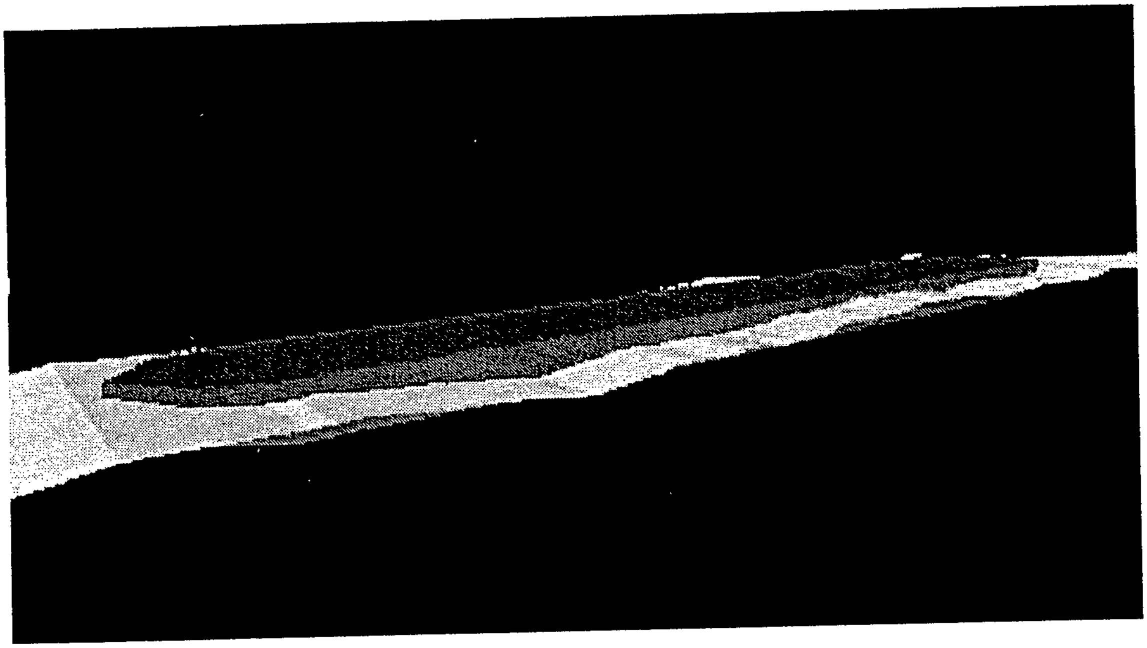

Figure 4. Barge in head seas, sea state 5.

Table 1 — Sea-Keeping Simulation Results

PARAMETER	RESULTS	
Sea State	5	8
Significant Wave Height, m (ft)	3.11 (10.2)	15.6 (51)
Modal Period, sec	7	16
Significant Pitch, deg	0.25	5.9
Significant Heave, m (ft)	0.15 (0.48)	3.83 (12.6)

Two factors contribute to the large difference in transporter performance in these two sea states: (1) the energy in sea state 8 is much greater than in sea state 5 and (2) as wave heights increase, the energy is more concentrated at the low frequencies where this large, heavy vessel responds.

Compartment Design

Each cargo compartment is 12 m (40 ft) long by 12 m (40 ft) wide by 6 m (20 ft) deep, containing 500–620 m^3 (660–800 yd^3) of dredged material. The compartment bottom door design utilizes two doors configured similar to a typical

split hull barge (Fig. 3). The doors are held shut with a locking mechanism and a secondary hydraulic support system while in transit. The weight of the dredged material aids the opening of the doors.

The requirements set for the release of the containerized dredged material aim at releasing the material quickly with minimal physical restrictions and stresses on the fabric container. The stresses on the container during release include: pressure of the dredged material against the compartment walls, frictional stresses between the container fabric and the compartment wall, hydrodynamic drag against the water, tension stresses owing to physical deformation of the container because of obstacles, and stresses due to the weight of the dredged material on the container and bottom doors. The stresses in the fabric were reduced: (1) by incorporating a freely flooded compartment; (2) fast, fully opening compartment doors; and (3) low friction, high density polyethylene (delrin) liners on compartment walls.

Dredged Material Container

Rupture of the container fabric and/or seams is the highest risk factor in the engineering concept. Since the fabric seams normally offer lower tearing strengths than virgin fabric, the container design/construction should minimize the number and length of seams. The recommended shape for the geosynthetic fabric containers (GFCs) is a spherical or ellipsoidal "pill-shape."

To avoid the possibility of container material floating to the sea surface, the specific gravity of the material should be greater than that of water. GFCs are currently made from polyester woven fabric with a specific gravity (S.G.) of approximately 1.3. Containers can be constructed using an outer permeable GFC with an inner impermeable polypropylene liner material (S.G. $\cong$ 0.91). Information on the use of GFCs to contain dredged material are found in Fowler (1995), Fowler et al. (1994), and Fowler et al. (1995). A summary of predicted polyester fabric performance in the abyssal ocean environment is reported by Valent and Young (1995, Sec. 1.4.2).

GFC DYNAMICS DURING RELEASE, FALL, AND IMPACT

Background

Sediment-filled Geosynthetic Fabric Containers (GFCs) have been placed from bottom-dump hopper barges in the Netherlands for coastal construction (Ockels 1991), in the U.S. for groin construction for channelizing river flow, and for containment of contaminated dredged materials (Fairweather 1995, Mesa 1995). To date, the GFCs have been dropped in water depth less than 30 m and are known to have experienced rupture or tearing problems during transport in hopper barges, release from barges, or impact on the bottom. The relocation of contaminated dredged material to the abyssal seafloor poses a problem of considerably different magnitude in that the filled GFCs will be free-falling through 5000–6000 m of water column over a time duration approaching 20 min and may impact on the seafloor at terminal

velocities considerably higher than the 5 m/sec noted to date. Extrapolating from the behavior of rain drops falling in air (Green 1997), the GFCs during free-fall are predicted to assume the shape of an oblate spheroid flattened in the vertical direction. Further, dynamic forces acting on the GFCs will cause changes of shape and redistribution of stresses that could exceed limits of the GFC fabric. Vortex shedding during free-fall is expected to cause second-order shape changes of the GFC, particularly near the periphery. These shape changes, coupled with the vortex shedding, could result in significant tilt of the GFC from the vertical and accompanying lateral skating of the GFC as it free-falls. This lateral skating could result in considerable deviation of the GFC from its ideal free-fall path, resulting in a larger disposal mound than the 3000-m diameter size estimated in Valent and Young (1995).

Analyses of the GFC dynamics during release from the transporter, free-fall through the water column, and impact on the abyssal seafloor were conducted with finite difference codes. Closed-form solutions of the free-fall portion of the analyses were performed to better understand and validate the free-fall finite-difference model.

Release of GFCs from Cargo Compartment

The simulation code used in modeling of GFC release from the cargo compartments is a discrete element code used by Dr. John Palmerton of the U.S. Army Waterways Experiment Station (WES) for simulations of containerized dredged material release from split hull barges. The Fortran code "nydrop.f" had been used for previous calculations by WES in support of demonstrations of the use of GFCs for shallow water applications. Code predictions of container fabric stresses and container fall rates have been validated by Dr. Palmerton against theory and field data from drops in shallow water for containers of fixed shape. The original Palmerton model was designed for use in a quiescent water column with an added capability for regions of constant current. It was assumed that motions of the GFC and contents would be governed by constant drag coefficients, and there was no provision to couple in externally supplied forces in dynamic calculations of the GFC motion. For releases in shallow water, where GFC lengths were on the same order as the water depth, these approximations were reasonable and could be bounded by experimentally derived error bars. For the calculations of bag descent and impact at abyssal depths, the external forces experienced by each discrete element (disks in the model) comprising the GFC wall would be different, and the resultant unsteady GFC shape changes and unsteady motions would be important factors in being able to determine the descent path of the GFC as well as the stresses experienced in the GFC wall. Therefore, modifications of the Palmerton code were necessary to provide the new unsteady forces at each timestep to each of the discrete elements comprising the GFC wall and contents. Iterations continued until a new GFC shape was assumed, and the new shape and position of the GFC were given as inputs to the gridding routines prior to the calculation of the new hydrodynamic forces.

The Palmerton model was modified to include several new capabilities: (1) vary geometry and rate of opening of cargo compartment bottom doors, thus enabling

input of data directly from detailed CAD simulations; (2) impart an initial vertical velocity to the GFC and its contents at release to account for the cargo compartment lowering/drop during the GFC release phase, and to incorporate the heave, pitch, and roll of the transporter derived from sea-keeping calculations; (3) provide for coupling the code to a hydrodynamic code for self-consistent calculation of the effect of the external flow on the GFC and its contents, including boundary layer formation, unsteady wake effects, and vortex shedding; (4) provide for coupling the GFC position and shape back to the automatic gridding codes for external hydrodynamics calculations; (5) provide for subiterating the Palmerton model in conjunction with the hydrodynamics codes; and (6) add output of the forces acting on the GFC and its contents for post processing, particularly for visualization of stresses in the GFC wall induced during release, descent, and impact. As part of the model modification, the IBM-specific WES code was converted to run on a SGI machine to permit incorporation into the overall DOR simulation capability. For details of the full coupling between the codes the see Valent and Young (1997) and Fitzpatrick et al. (1997).

Free-Fall of GFC to Seafloor

The development of a predictive model describing the free-fall descent of a GFC enclosing 300 to 800 m^3 of dredged material through 5000 m water column, without benefit of model or prototype performance data of applicable scale, was undertaken along two paths. One of the authors (AWG) approached the problem via a closed form analytical approach combined with empirical data used to set some critical parameters, while Dr. Martin Fritts, SAIC-Annapolis, led a team applying a Reynolds-Averaged Navier-Stokes (RANS) solver to the problem.

Closed-Form Solution for Simplified Shape for Free-Falling GFC

The conceptual model for a dredged material-filled GFC is a fluid-filled membrane which has a shape determined by the local balances of hydrodynamic, hydrostatic and membrane forces. The 'real' case should take account of local force balances at all points on the container and the variability of these balances due to deformation of container by fluctuations in the turbulent wake. The pressure at the bottom flow separation zone will tend to flatten the container, and the shape will be roughly ellipsoidal, if there is sufficient membrane stress to keep the interior fluid mass intact. Further, it is known that the hydrodynamic pressure must equal the ambient far-field value somewhere between the base of the container and its trailing edge. The most basic assumption in this model is that the shape is an oblate ellipsoid; this is an approximation of the equilibrium shape of the GFC.

The following analysis is based on the assumption that the fluid-filled flexible container is constrained to the shape of an oblate ellipsoid that is deformed by the hydrostatic forces. Measurements of the pressure distributions around oblate ellipsoidal bodies at high Reynolds numbers and terminal fall speed show that the pressure is

near the far-field ambient value in the vicinity of the equator. For the case of a fluid-filled membrane, this allows an additional assumption: the hydrostatic force and intrinsic pressure force are balanced by a membrane tension force evaluated at the equator. The flattening of the ellipsoid increases the surface area and decreases height so that the internal hydrostatic pressure is balanced by the wall tension. The degree of flattening of the ellipsoid can be shown to be a function of the Bond number, $B=\sigma^{(-1)}\left(1-\dfrac{\rho_w}{\rho_c}\right)\rho_c\, g\, a_0^2$:, or more properly for the case of GFCs, a function of the bulk wet density of the GFC contents, ρ_c, where σ is the wall tension parameter, ρ_w is the density of the water surrounding the GFC, g is the acceleration of gravity, and $a_0{}^2$ is the radius of a sphere with volume equal to the ellipsoid. Fig. 5 is a set of superimposed ellipses representing the meridional cross sections of ellipsoids for the cases of Bond Numbers B = 0, 1, 2, 3, 4, 10, 150. The Bond number is the critical parameter in determining the shapes of the bags. If equivalent spherical radii are in the range 4–7 m and the container contents bulk wet density ranges 1.4–1.7 Mg/m^3, then the Bond numbers will be ~ 0.33–3.69. Over that range of B, the axis ratio of the ellipsoid decreases from ~5/6 to ~1/2. The lower values of B indicate a relatively "tight form," but the upper extreme values could be marginal for wake-induced shape instabilities.

In the observed cases of low Bond number, fluid-filled bodies are flattened, or concave downward, and are not symmetric about the equatorial plane. These surfaces would be described in terms of variables at somewhat higher degree than quartics; however, their thickness-to-width ratios are similar to oblate ellipsoids.

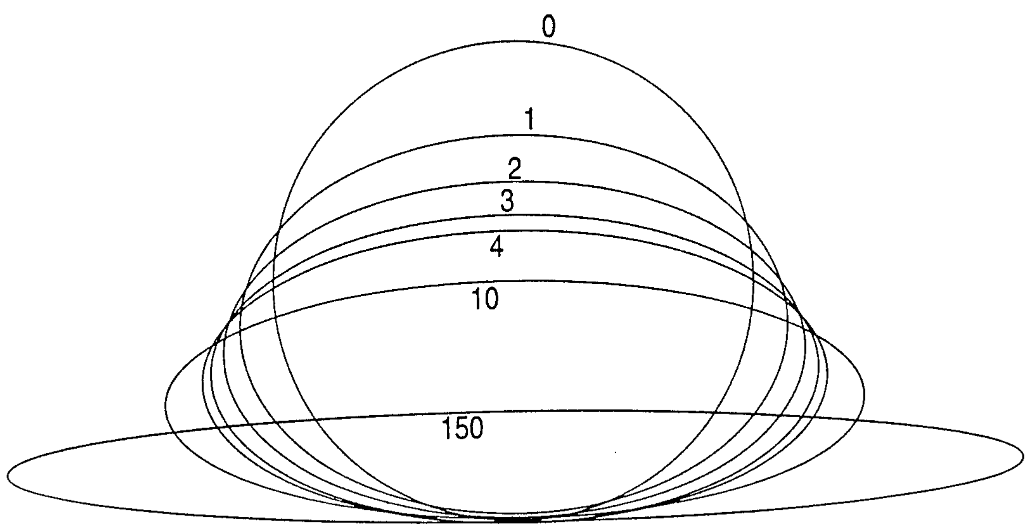

Figure 5. Shape of the ellipsoid with increasing Bond No. 0, 1, 2, 3, 4, 10, 150.

When a bluff body such as a GFC moves through a fluid rapidly enough that purely viscous forces are not significant [large Reynolds Number R= (*Length Scale of Body × Velocity through the Fluid/Kinematic Viscosity*)], the wake becomes unstable and a stream of vortices are shed behind the body. The rate of vortex shedding is represented by the Strouhal Number (S). Considerable data exist about the shedding frequencies behind a variety of rigid body shapes, but there is no comprehensive analytical (or numerical) models that can accurately approximate the dynamics for arbitrary body forms. Therefore, this analysis uses the compilation of empirical results in *Fluid Dynamic Drag* by S. F. Hoerner.

The results of the combination of Hoerner's empirical model with the hydrostatically deformed ellipsoid and terminal fall speed models are self-consistent. The interpretation is simple: (1) the higher the Bond number – the flatter the ellipsoid; (2) the flatter the ellipsoid – the slower it falls; (3) vortex shedding frequencies from low-tension, smaller ellipsoids are higher than larger, stiffer ones. The shedding frequencies range from about 0.2 Hz for a small (4.8 m equivalent radius), lower density (1.4 Mg/m^3), stiff (800 N/m) tension bag to 0.32 Hz with the flaccid, smaller bag with higher density (1.7 Mg/m^3).

These models do not take into account the fact that the dynamics of flow will distort the flexible GFC into non-symmetrical shapes and that these deformations may drastically affect the flight trajectory of the body. Fortunately, if the GFCs are flaccid, off-axis hydrodynamic lift will tend to redistribute the materials in the bag. Modal oscillations are expected to have lower frequencies than the shedding frequency, so resonances would be unlikely. If the bag is too flaccid (very high Bond number), it will not be able to maintain a predictable form, since the restoring force of wall tension will be ineffective. Twisted or isolated lobe shapes could result. In such cases, local stresses could tear the bag – particularly at the time of bottom impact.

This analysis has been based on empirical formulae, an axi-symmetric body shape and an approximation of wall, dynamic and hydrostatic balance at a single latitude of the ellipsoid. The differential geometry of the system, even in this simplified case, produced highly nonlinear expressions that had to be approximated. However, the model results do appear reasonable. These models do not take into account the fact that the dynamics of the flow will distort the container into non-symmetrical shapes and that these deformations may drastically affect the flight trajectory of the body. Fortunately, in the real case, the GFCs will not be too flaccid; consequently, non-symmetric off-axis hydrodynamic lift will tend to be redistributed by shifting of the materials in the GFC, wall tension and hydrostatic forces.

Finite-Analytic Reynolds-Averaged Navier-Stokes Solution for Free-Falling GFC

A successful GFC drop simulation scheme must accurately account for (at least) three highly complex fluid flow phenomena: GFC wall stress prediction, GFC trajectory predictions, and impact plume prediction. All three problems require solution of the complete, unsteady, turbulent flow around the GFC. Wall stress predictions

require a local distribution of forces. Trajectory prediction requires unsteady integrated forces and moments caused by both attached boundary layers and separated turbulent wakes. Plume prediction requires the ultimate level of knowledge of flow, including the complete flow field description around a GFC as it impacts on the seafloor.

The minimum level of Computational Fluid Dynamics (CFD) technology capable of providing all the necessary information for turbulent, vortical flows is the class of Reynolds-Averaged Navier-Stokes (RANS) solvers. This section of the paper describes the adaptation and application of one such solver, the Finite-Analytic Navier-Stokes (FANS) system to the GFC free-fall problem. FANS is a proprietary, well-validated, three-dimensional, unsteady, incompressible RANS code applicable to a wide range of high-Reynolds number steady and unsteady flows (Korpus 1995, Chen and Korpus 1993, Weems et al. 1994). (Note: While the RANS code is capable of three-dimensional analyses, funding constraints limited application to the GFC free-fall problem to two-dimensional geometries.) The FANS code supports body fitted, multi-block, overset (a.k.a. Chimera) grids, and can therefore resolve any flow domain with maximum grid quality. The code utilizes the finite-analytic technique for primitive velocity and turbulence quantities, and a SIMPLER/PISO non-staggered Poisson solver for pressure. FANS currently employs three state-of-the-art turbulence models: a modified *ke* (Hanjalic and Launder 1990); a non-linear algebraic Reynolds stress model (Gatski and Speziale 1993); and a fully implicit seven-equation Reynolds stress model (Speziale, et al 1991). Two techniques are available for solving the turbulent dissipation rate equation: a two-layer model that assumes a prescribed algebraic distribution in the near-wall region (Chen and Korpus, 1993); and a low Reynolds number extension technique that solves e all the way to the wall (So, Zhang, and Speziale, 1991). Either technique can be used with each of the three models to provide a full range of turbulence capability.

Two aspects of the GFC free-fall modeling are unique: the need to couple fluid forces to GFC dynamics; and the need to couple fluid forces to GFC shape. While these aspects do not require complex capability development in the traditional sense, they do require the integration of capabilities which are complex in their own right. Coupling of GFC dynamics to the fluid forces, for instance, requires that the portion of grid which is fixed to the body be moved according to the equations of motion of the GFC. Thus, each time step requires solution of a solid-body dynamics equation for every degree-of-freedom of body motion.

FANS was applied to simulate the free-fall of GFCs, first computing the flow and resulting forces on the GFC, and then integrating to update the GFC velocity and position. After each update, the grid is regenerated, and the process repeated. Since experiments at the WES had indicated that bag shape is fairly constant and fairly elliptical, it was decided to use a 6 to 10 ellipse to represent the idealized GFC. A further advantage of this decision is that the University of Manchester steady-state ellipse data could be used as a "sanity" check. The simulation was performed using a GFC of 12.5 m beam and 7.5 m depth. Bulk wet density of contents was assumed uniform at 1.7 Mg/m^3. The initial attitude of the GFC was with long axis horizontal, and its initial horizontal, vertical, and roll velocities were

specified as 0.3 m/sec, 0 m/sec, and 0 rad/sec, respectively. The test domain was limited to a section of ocean 300 m wide and 300 m deep in order to keep CPU times at reasonable levels. The computation was non-dimensionalized using a characteristic length of 12.5 m, and characteristic velocity of 4.6 m/sec.

The grid contained about 80,000 points in four blocks, and 10,000 time steps were used to complete the 36 sec long drop time. Records of velocity and pressure were kept for every 40th time step for a total archive size of 209 megabytes. Video records were generated for pressure, vertical component of velocity, and vorticity. Two frames from the video record, one 10 sec into the drop and one 30 sec into the drop, are shown in Fig. 6. The unsteady wake expected from the von Karman vortex street is visible, and the asymmetric forces resulting cause the body to pitch and translate horizontally. The 30 sec frame shows that the GFC leaves behind some significant "down-drafts" as it cycles through its periodic horizontal motion. For the above initial conditions, FANS predicted GFC roll up to 40 degrees, horizontal translation of 30 m (over 300 m fall), and average fall velocity of 9 m/sec (see Fitzpatrick et al. 1997).

Experimental Results for Free-Falling GFC

While planning and conducting the analytical studies above, models were selected and assumptions made regarding the physics of GFC behavior during free-fall that were directing the outcome of the predictions. No data were known describing the dynamics of fluid-sediment-filled membrane-like containers in free-fall in a fluid. The geometries possible for the free-falling GFC were not known with certainty, and, therefore, the terminal velocity was unknown. The studies above suggested that the GFCs in free-fall will oscillate and have erratic trajectories, but the distribution of impact points about a seafloor target was uncertain as was the significance of the downwash from added water mass and ejection of trapped water from beneath the impacting GFC. Project participants were uncertain of the validity of predictions and decided to conduct a low-budget, short-timeframe experiment to better understand the physics being modeled.

To obtain answers to these questions, an experiment using model GFCs was conducted in a 10.7 m deep by 11.3 m diameter water-filled tank maintained by the National Marine Fisheries Service, NOAA, at Stennis Space Center. Large latex rubber balloons were employed as model GFCs filled to a nominal spherical diameter, a_0, of 0.12 m with a combination of near-spherical glass beads of 0.5-1.0 mm diameter. Three balloons were filled with combinations of water and glass beads to achieve contents of bulk wet density of 1.1, 1.4, and 1.7 Mg/m^3. Water-filled ping-pong balls and golf balls were arrayed about the center of the tank bottom to serve as indicators of water jets/plumes resulting from GFC impact on the bottom. Two video cameras, one on a stand at the bottom and viewing the center-bottom of the tank, the other diver-held to follow the balloon descents, were used to record time, displacements, and bottom impact locations (Fig. 7). The model GFCs were all released for free-fall from a hand-held position just beneath the water surface.

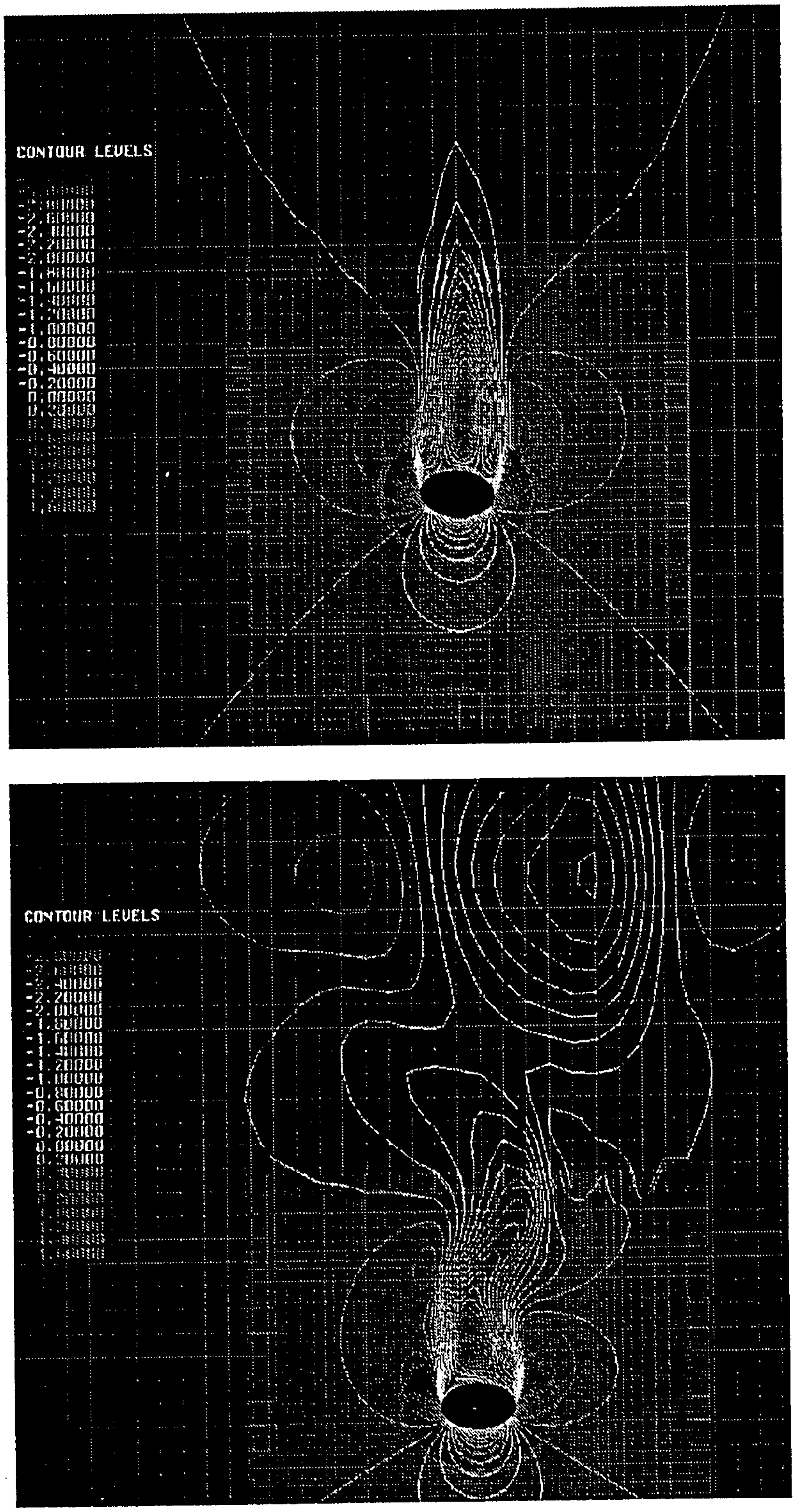

Figure 6. Contours of vertical velocity around GFC during free fall.

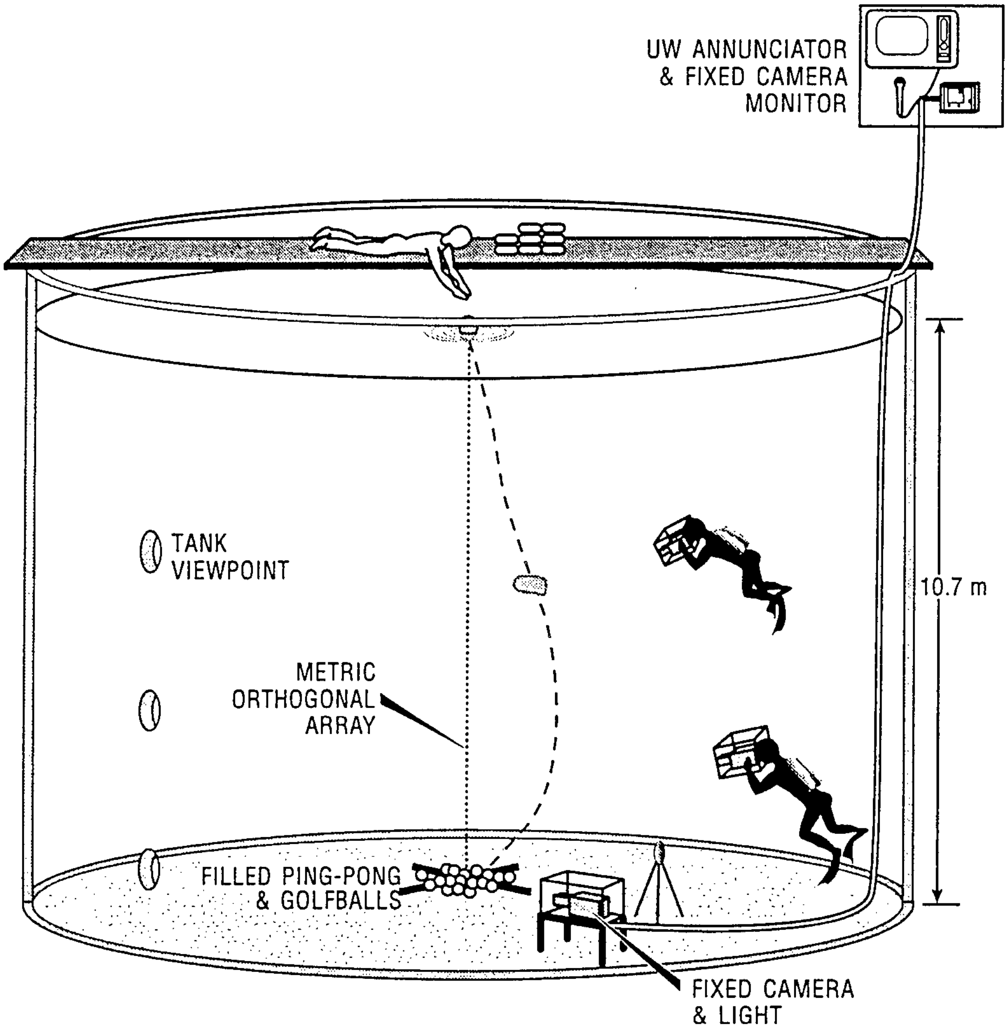

Figure 7. Bag drop experimental configuration.

Data from the video provided for calculation of thickness ratios during free-fall of about 1.1 for the lightest loaded model (1.1 Mg/m^3), about 0.8 for the intermediate (1.4 Mg/m^3), and 0.65 for the heaviest loaded model (1.7 Mg/m^3), confirming the trend prediction reported earlier. Contrary to analytical predictions, the free-falling model GFCs did not demonstrate significant oscillations in pitch. Rather, the heaviest loaded model, for which the greater number of drops were made (12 drops), fell about one balloon diameter during which time the balloon assumed its flattened ellipsoid shape, and then pitched about 20 degrees and traversed a helicoidal/spiral path that came close to completing one full cycle in the 10.7 m fall (Fig. 8). If there is dynamical similarity in the trajectory of the model GFCs and the prototype, then the prototype GFCs would complete 6–7 cycles of the spiral in their 5000 m fall.

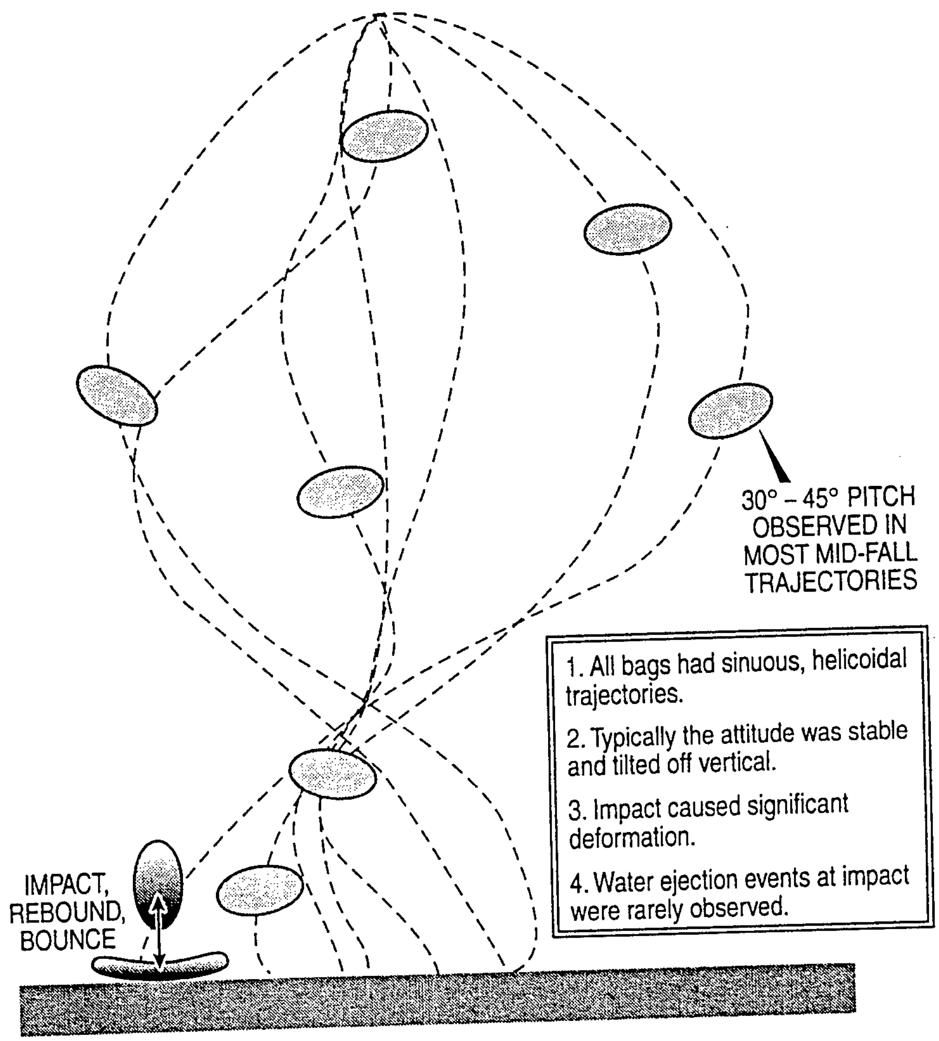

Figure 8. Bag fall trajectories and attitudes.

The observed steep diving trajectory of the model GFC is of great significance in predicting the size required for a seafloor isolation site for the GFCs. Direct extrapolation from the 12 drops of the heaviest GFC model suggests that the average radius of the seafloor impact site, barring all other sources of deviation, would be 530 m, and the extreme radius would probably be about 1200 m. Given the possibility non-symmetrical distribution of mass within the GFCs in the real world case, and given the limited data on which the earlier extrapolation is based, a conservative estimate of 2500 m radius for the impact zone is being used in a subsequent project researching the monitoring system to be used for the deep ocean relocation option.

One further data item observed during the model GFC drop tests was the failure to detect focused water jets with impact of the model GFCs on the tank bottom. In only one instance were the balls near the tank center moved concurrent

with model GFC impact. The video data suggest that the model GFCs impacted the tank bottom in 20 degree leading-edge-down attitude and then rolled/flopped down to a horizontal position after leading-edge impact. The water jet noted appeared to be generated by the flop-down of the model, and appeared to be directed out from beneath the high side of the GFC as it flopped down.

PENETRATION/EMBEDMENT OF GFC AND CONTENTS IN SEAFLOOR

The surface seafloor sediments at likely abyssal sites for dredged material isolation will be hemipelagic or pelagic clays with a thin surficial layer, 5–15 cm thick, of bioturbated sediments with a steeply increasing undrained shear strength profile with depth (Rocker 1985). This surficial layer will be underlain by sediments with a profile of gradually decreasing water content and gradually increasing undrained shear strength (Rocker 1985). The impact on and penetration of the 300–800 m^3 of dredged material contained in the GFC will be resisted by the inertia of the seafloor sediment mass being displaced and by the undrained shear strength (dynamic undrained strength) along developed shear zones.

A predictive model for this impact/penetration phenomena is available (Rocker 1985, Chapter 8) but was not used and validated because effort was concentrated on the GFC release and free-fall phenomena model validation. The penetration prediction model was developed for rigid objects penetrating into a seafloor of unconsolidated sediments, either cohesive (clays, silts, muds) or cohesionless (sands). The application of the technique model to the description of penetration of a flexible (but incompressible), fluid-like dredged material filled bag would be considerably more involved than the method described in Rocker, to account for the deformation of the bag contents and associated redistribution of bag–seafloor contact pressures during penetration. The method in Rocker 1985, accounts for decelerating forces due to the density difference between the penetrator and the media being displaced, the inertial forces generated in accelerating sediment during penetration, and the resistance of the sediment to shearing.

CONCLUSIONS

1. The isolation of contaminated dredged materials on the abyssal seafloor, from the process of clean dredging through containerization, transport, and placement on the seafloor, is shown to be technically feasible through analytical modeling and preliminary component and system design.

2. The Integrated Tug-Barge (ITB) concept is shown in sea-keeping analyses to perform well in sea states up through 5. In sea state 8 the ITB performance is shown to be not acceptable, requiring the tug-pushing-the-barge arrangement to be changed to a tug-towing-the-barge configuration.

3. Geosynthetic fabric containers (GFCs) of length equal to width, properly filled, will traverse steeply-descending, irregular, generally helicoidal (or spiral) paths in free-falling through any significant water depth (greater than 2–4 GFC thicknesses).

4. Although the particular path of any one GFC in free-fall is not predictable, the free-fall speed and the wall stresses, including dynamic stresses, in the GFC can be predicted to sufficient resolution for GFC design.

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